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Seismotectonics

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INTRODUCTION

Seismotectonics is the synthesis of earthquake, geophysical, geodetic and geological data to deduce the tectonic framework of a region [Scholz, 1990]. This approach has been applied successfully to active tectonic regions such as plate boundaries, regions of intraplate seismicity, and active volcanoes throughout the world.

Because more than 85% of the seismic moment release takes place in subduction zones [Scholz, 1990], these have abundant large and great earthquakes and are by far the most popular study regions. The second most popular study region is the state of California, because the transform boundary, the San Andreas fault, is on land and easily accessed [Wallace, 1990]. Studies of earthquakes along the San Andreas fault system include the 1987 (M_S=6.6) Superstition Hills and the 1989 (M_S=7.1) Loma Prieta earthquake. During the last four years seismotectonic studies have also lead the way in studying fold and thrust belts in California. Two significant concealed thrust faulting earthquakes, the 1983 (M_S=6.7) Coalinga and the 1987 (M_L=5.9) Whittier Narrows earthquake have provided ample data for these studies. The 1988 (M_S=6.8) Armenian earthquake is another example of a damaging partially concealed event, occurring along the southern edge of the Lesser Caucasus where the north-south convergence occurs at 30 mm/yr [*Pacheco et al.*, 1989]. Seismotectonic studies of earthquakes in the central and eastern U.S. are of significant interest to U.S. researchers because this region has a probability of approximately two-thirds that of California to have an earthquake with similar damage in the next 30 years [*Nishenko and Bollinger*, 1990]. Volcanic seismicity is also of interest because volcanic eruptions in Hawaii and Alaska continue to be associated with significant earthquake sequences. Volcanic seismicity also provides an important means to mitigate volcanic hazards and insights into the physics of near-surface magmatic processes.

In this report that covers the U.S. contributions to seismotectonics during 1987-1990 I have followed the organizational approach of Hill [1987]. I discuss only some of the interesting advances, while many more studies are also documented by the papers listed in the bibliography.

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CALIFORNIA'S TRANSFORM BOUNDARY

San Andreas Fault System

Studies of the San Andreas fault itself have included analysis of individual earthquake sequences and synthesis of data from significant stretches of the fault. The debate over the strength of the fault continues although recent analysis of borehole breakout data and earthquake focal mechanisms suggest that the fault in central California is weak and dip-slip motion is partitioned onto adjacent subsidiary faults [*Mount and Suppe, 1987*; *Zoback et al.*, 1987].

Improved dates of great earthquakes along the Mojave segment of the San Andreas fault indicate that the past 10 earthquakes occurred in four clusters, each with two or three events [*Sieh et al.*, 1989]. Trenching and measurements of the deformation of a drainage canal along the southern San Andreas fault in Coachella Valley revealed evidence for both low creep rates of 2-4 mm/yr and large prehistoric earthquakes [*Sieh and Williams*, 1990]. A re-evaluation of historic aseismic, post seismic and seismic slip along the Parkfield segment of the San Andreas fault showed that a slip deficit of 3±0.2 m exists south of Gold Hill and only 0.3±0.3 m deficit exists to the north of Parkfield [*Segall and Harris*, 1987; *Lienkaemper and Prescott*, 1989]. Further north of Parkfield along the creeping segment of the fault *Perkins et al.* [1989] found a slip rate of 22±6 mm/yr. They attributed the northwestward decrease in long-term slip rate to transfer of slip to the Paicines and Calaveras faults. In northern California the evolution of the San Andreas fault system could be controlled by thermal-mechanical processes associated with the development and evolution of a narrow "slabless window" moving along the western edge of North America [*Furlong et al.*, 1989].

Bilham and King [1989] explained the morphologies of the Parkfield region and the Coachella segment with simple distributions of slip on mapped surface faults. Using high quality borehole microearthquake data to image the Parkfield asperity, *Malin et al.* [1989] showed that the asperity or the strong patch along the fault, is devoid in microearthquakes and stress drop of earthquakes is higher immediately adjacent to this zone.

Oppenheimer et al. [1988] used 946 fault plane solutions of aftershocks of the 1984 Morgan Hill earthquake to infer a high-angle uniform stress field along the Calaveras fault. They combined this stress field with changes in the static stress field caused by the mainshock and were able to explain the focal mechanisms and spatial distribution of aftershocks.

Jones [1988] used 138 focal mechanisms of small earthquakes to invert for the state of stress along the San

Andreas fault from Parkfield to the Salton Sea. She found remarkable agreement between the state of stress derived from the focal mechanisms and the late Quaternary geologic deformation along the fault. In a more regional study *Sanders* [1990] interpreted the depth distribution of small earthquakes in southern California and showed that the depth of faulting is greater within major fault zones than within the adjacent, more stable crustal blocks.

The 1986 North Palm Springs earthquake in southern California occurred on the San Andreas fault and both aftershock locations as well as local and teleseismic focal mechanisms showed that the San Andreas dips 50° to the northeast in Banning Pass [*Jones et al.*, 1986; *Pacheco and Nabelek*, 1988]. A finite fault inversion for slip distribution along the fault plane of the 1986 North Palm Springs earthquake revealed a 6x4 km^2 patch of large magnitude oblique reverse slip and a 3x5 km^2 patch of large magnitude right-lateral strike-slip [*Mendoza and Hartzell*, 1988]. Aftershocks with high stress drops were observed outside or near the edges of these patches of large magnitude slip [*Mori and Frankel*, 1990]. Following the mainshock, *Williams et al.* [1988] reported aseismic triggered slip 44 to 86 km to the southeast along the San Andreas fault.

A moderate-sized thrust faulting earthquake (M_L=5.3) occurred offshore in July 1986, near Oceanside in the Continental Borderland [*Hauksson and Jones*, 1988; *Pacheco and Nabelek*, 1988]. Either the thrust faulting may be caused by a left step in the San Diego trough fault or thrust faulting is more common within the Continental Borderland than previously thought [*Legg et al.*, 1989].

The 1987 (M_S=6.6) Superstition Hills earthquake sequence consisted of a foreshock sequence (M_S=6.2) on the northeast striking Elmore Ranch fault and the mainshock-aftershock sequence on the northwest striking Superstition Hills fault [*Magistrale et al.*, 1989; *Hanks and Allen*, 1989]. Modeling of both teleseismic and strong motion data shows that the mainshock rupture was complex and consisted of at least two or three subevents [*Hwang et al.*, 1990; *Bent et al.*, 1989; *Frankel and Wennerberg*, 1989; *Sipkin*, 1989; *Wald et al.*, 1990]. The largest foreshock was accompanied by 9 km long surface rupture along the Elmore Ranch fault and the mainshock was accompanied by a 27 km long surface rupture along the Superstition Hills fault [*Sharp et al.*, 1989; *Bilham*, 1989; *Hudnut et al.*, 1989; *Williams and Magistrale*, 1989; *Sharp and Saxton*, 1989; *Klinger and Rockwell*, 1989; *McGill et al.*, 1989]. The cross fault interaction observed in the 1987 Superstition Hills sequence may be a possible triggering mechanism for future earthquakes along the San Andreas and San Jacinto faults [*Hudnut et al.*, 1989].

Central Coast Ranges

Studies of the 1982 (M_W=5.4) New Idria, 1983 (M_W=6.5) Coalinga and 1985 (M_W=6.1) Kettleman Hills earthquakes in the central Coast Ranges have greatly enhanced our understanding of the earthquake potential of fold and thrust belts. The Coalinga earthquake was the largest of the three, and its seismological, geological, and engineering aspects are described in U.S. Geological Survey Professional Paper 1487 [e.g., *Rymer and Ellsworth*, 1990; *Eaton*, 1990]. *Namson and Davis* [1988] applied the technique of balanced cross section to explain how the 1983 Coalinga earthquake contributed to the growth of the Coalinga anticline. *Eberhart-Phillips* [1990 and 1989] determined the three-dimensional velocity structure of the Coalinga region and used it to constrain the pattern of active faulting and deformation in the Coalinga area. She demonstrated that the faulting consisted of southwest dipping thrusts uplifting blocks of higher-velocity material. The Coalinga mainshock caused the maximum principal stress to rotate 15° to the north [*Michael*, 1987].

The *Eaton and Rymer* [1990] model for thrust faulting earthquakes in the southern Coastal Ranges attributes the thrust events to a component of apparent convergent displacement across the San Andreas fault. The model also suggests that both possible ramping up of detachment zones into the brittle crust and presence of strong crustal blocks will contribute to occurrence of great earthquakes in this region.

In a more regional study *Wong et al.* [1988] argued that the whole length of the northern and central Coast Ranges-Sierran block boundary zone was seismically active. They provided three possible explanations for the compression within this zone: 1) the westward motion of the Sierran block against the Coast Ranges; 2) slightly convergent motion along the plate boundary; 3) fault-normal compression across a weak San Andreas fault. Thrust faulting earthquakes also occur west of the San Andreas fault in the Coast Ranges, central California [*Dehlinger and Bolt*, 1987].

Transverse Ranges

Studies of the seismotectonics of the Transverse Ranges are mostly based on analysis of seismicity, GPS (Global Positioning System) and other geodetic data, heat flow data, and geological studies of individual fault segments. Using a combination of data from local earthquakes, teleseisms, and seismic refraction surveys *Keller and Prothero* [1987] showed that crustal thickness increases from 23 km thick in the Borderland to 31 km thickness beneath the western Transverse Ranges. Estimates of fault slip-rates based on models of block motion within the Transverse Ranges inferred from geodetic data in most cases show good agreement with geological estimates [*Cheng et al.*, 1987]. *Feigl et al.* [1990] used GPS and geodetic data to show that 7 mm/yr of convergence is taking place across the Santa Maria fold and thrust belt in the western Transverse Ranges.

The Ventura Avenue anticline is shortening at a rate of about 9 mm/yr since its inception [*Rockwell et al.*, 1988]. This shortening is associated with low heat flow in the Ventura basin compared with the rest of southern California [*De Rito et al.*, 1989]. The San Cayetano fault is a major, north-dipping reverse fault on the north side of the Ventura basin, which has a slip rate possibly as high as 7 mm/yr and is capable of generating damaging earthquakes [*Cemen*, 1989; *Rockwell*, 1988].

A comparison of the seismotectonics of the Transverse Ranges and the South Island, New Zealand is provided by *Yeats and Berryman* [1987]. They find many similarities in terms of seismicity and modes of faulting between both the main strike-slip plate boundary fault and the deformation occurring away from the boundary.

Los Angeles Basin

The 1987 (M_L=5.9) Whittier Narrows earthquake provided a new perspective on the tectonics and in particular compressive structures in the Los Angeles basin [*Hauksson et al.*, 1988]. Previously these structures had been thought to be secondary features associated with the northwesterly strike-slip faults such as the Newport-Inglewood fault or compressional tectonics of the Transverse Ranges which extended into the basin [*Hauksson*, 1987]. Long-period and short-period seismic, geodetic, and geologic data collected during and following the Whittier Narrows earthquake all showed that the event occurred on a concealed thrust fault and that the coseismic deformation caused the fold above the hypocenter to grow by 5 cm [*Hauksson and Jones*, 1989; *Bent and Helmberger*, 1989; *Lin and Stein*, 1989; *Davis et al.* 1989].

The compressional tectonics observed in the Whittier Narrows extend to the west into Santa Monica Bay [*Hauksson and Saldivar*, 1989]. The first evidence in support of the existence of a possible detachment surface beneath the Los Angeles basin was presented by *Langston* [1989]. He used teleseismic receiver functions to show that a low velocity layer, corresponding to meta-sediments, exists at a depth of about 20 km and dips gently to the north under the San Gabriel Mountains.

In a comprehensive analysis of the focal mechanisms of 244 small earthquakes in the Los Angeles basin, *Hauksson* [1990] showed that strike-slip, thrust and normal faulting earthquakes all occur in the Los Angeles basin. He suggested decoupling of right-lateral strike-slip and dip-slip motion as a means of merging the strike-slip tectonics of the Peninsular Ranges and thrust tectonics of the Transverse Ranges in the Los Angeles basin. The 1988 Pasadena earthquake was interpreted to be caused by left-lateral slip on the east-northeast striking Raymond fault [*Jones et al.*, 1990; *Kanamori et al.*, 1990].

The 1989 Loma Prieta Earthquake

The most studied earthquake in recent times is the 1989 M_S=7.1 Loma Prieta earthquake [e.g., *U.S. Geological Survey Staff*, 1990; *McNally and Ward*, 1990]. These studies are focused on the seismological, geological, and engineering aspects of the earthquake. Focal mechanisms as well as other source parameters obtained from local seismic network data, P_{nl}-waves, long-period body waves and surface waves are similar and show right-lateral strike slip motion with a significant reverse component [*U.S. Geological Survey Staff*, 1990; *Kanamori and Satake*, 1990; *Choy and Boatwright*, 1990; *Ruff and Tichelaar*, 1990; *Zhang and Lay*, 1990; *Houston*, 1990; *Barker and Salzberg*, 1990; *Langston et al.*, 1990]. At least three bursts of energy were recognized in teleseismic records corresponding to three subevents [*Choy and Boatwright*, 1990]. High-velocity P-wave and high-resistivity anomalies may correspond to the asperities that broke in these subevents [*Eberhart-Phillips et al.*, 1990; *Lees*, 1990].

The large reverse component implied a higher rate of uplift of the Santa Cruz Mountains than was actually observed and thus the slip surface of the Loma Prieta earthquake is not the main plate boundary fault [e.g., *Kanamori and Satake*, 1990]. A comparison between the coseismic uplift caused by Loma Prieta earthquake and the age of offshore marine terraces along the Santa Cruz coastline yields a maximum long-term uplift rate of 0.8 mm/yr [*Anderson*, 1990].

Most of the aftershock focal mechanisms were not similar to the focal mechanism of the mainshock and thus only a few of the aftershocks occurred on the mainshock slip plane [*Oppenheimer*, 1990]. A stress inversion of these focal mechanisms by *Michael et al.* [1990] showed that these aftershocks were not caused by a uniform tectonic stress field but rather by stress inhomogeneities around the mainshock rupture.

In the preceding 10 to 20 years of background seismicity there was no evidence for the existence of the southwestward dipping Loma Prieta rupture surface [*Olson*, 1990; *Seeber and Armbruster*, 1990]. The Loma Prieta earthquake, however, was preceded within 1.6 years by increased earthquake activity along secondary faults such as the Lake Elsman burst of seismicity [*U.S. Geological Survey Staff*, 1990; *Seeber and Armbruster*, 1990]. A seismotectonic model involving fault interaction between the San Andreas and the Sargent-Berrocal faults can explain coseismic displacement, preshocks, aftershocks, and the topography [*Schwartz et al.*, 1990].

INTRAPLATE REGIONS

While much progress has been made in terms of understanding seismic moment release and deformation along plate boundaries [e.g. Ekstrom and England, 1989], the rate of deformation and hence research progress is slower within the continental interiors. The large number of earthquakes occurring in the western U.S. facilitates systematic studies of the relationship between earthquake occurrence and Quaternary faulting, while in the central and eastern U.S. the lack of data makes it difficult to find such relationships.

Western United States

Fifty large earthquakes occurring from 1915 to 1988 in the Cordillera of the western U.S. were caused by slip on faults dipping 38° or more. More than 70% had unilateral rupture, and the largest subevent had a length of 20 km [*Doser and Smith*, 1989]. Another review of seismicity and late Quaternary faulting of the northern Basin and Range province, in Montana and Idaho shows geographic correspondence between epicenters of M>5.5 earthquakes and late Quaternary faulting [*Stickney and Bartholomew*, 1987]. They also showed that the three largest earthquakes located north of the Snake River Plain indicate three different stress provinces - the 1983 Borah Peak earthquake occurred in the Montana-Idaho Basin and Range; the 1959 Hebgen Lake earthquake occurred in the Yellowstone hot spot area; and the 1925 Clarkson Valley event appears to be associated with the stress field of the U.S. mid-continent. Modeling of geodetic data and lake shoreline changes shows that the 1959 Hebgen Lake earthquake had 3- to 4-fold higher slip than the 1983 Borah Peak and other large Basin and Range earthquakes [*Barrientos et al.*, 1987].

Instrumentally and non-instrumentally located seismicity for the eastern Snake River Plain shows that the Plain is relatively aseismic as compared with the adjacent block faulted mountainous areas. Microearthquake activity occurs only along the northeast-trending longitudinal axis of the Plain [*Pelton et al.*, 1990].

Historically the Nevada Seismic Zone has been the most seismically active region in the intermountain west. Most of the large events such as the 1915 (M=7.6) Pleasant Valley, 1932 (M=7.2) Cedar Mountain, and 1934 (M=6.5) Excelsior Mountain earthquakes exhibited either strike-slip or normal motion [*Doser*, 1988].

Fault slip data from Hampel Wash area, Nevada correspond to a modern least compressive horizontal stress azimuth of N50°-70°W inferred from earthquake focal mechanisms, well bore breakouts, and hydraulic fracturing measurements in the vicinity of Nevada Test Site [*Frizzell and Zoback*, 1987]. Similarly, Holocene displacements and slip rates of 2-2.7 mm/yr along the southern Panamit Valley fault zone provide evidence for relatively constant tectonics in the region over the last 4 million years [*Zhang et al.*, 1990].

Recent studies of late Quaternary surface faulting and displacement of crustal blocks in the Basin and Range show that the distribution of slip along strike is nonuniform [*Wallace*, 1987]. Extensional accommodation zones control the lengths of surface faulting events, which occurred on range-bounding Quaternary faults [*Thenhaus and Barnhard*, 1989].

In the northern Basin and Range province significant variations both in principal stress orientations and magnitudes occur [*Zoback*, 1989]. Least principal stress axes are aligned east-west along the margins, but are NW to N60°W in the interior parts. She also found that the temporal variations in the relative magnitudes of principal stress axes may occur on the time scales of both single and multiple earthquake cycles.

Small to moderate magnitude earthquakes occur at a low rate within the Colorado Plateau [*Wong and Humphrey*, 1989]. The largest earthquakes of M=5-6 occur in northern Arizona. The faulting consists of normal faulting on northwest to north-northwest striking faults, and the state of stress exhibits northeast extension.

Borah Peak earthquake. The 1983 (M_S=7.3) Borah Peak earthquake that ruptured a 75 km section of the Lost River fault is the most recent significant intraplate earthquake to occur in the western U.S. [*Richins et al.*, 1987]. Complex intersection of adjacent faults may have influenced the site of rupture initiation and also may have stopped the spreading of the rupture to the southeast [*Susong et al.*, 1990]. The region around the Borah Peak mainshock was aseismic at least 10 to 20 years prior to the mainshock [*King et al.*, 1987; Dewey, 1987].

The Lost River fault has a long history of normal faulting during the Quaternary. *Hanks and Schwartz* [1987] suggested that the earthquake, which preceded the 1983 Borah Peak earthquake occurred 6000 to 8000 yr before present. Subsequent data on the geochronology of upper Quaternary units show that the event preceding the 1983 earthquake occurred anywhere from 6850 to 530 yrs ago [*Cluer*, 1988].

Central and Eastern United States

The seismicity, neotectonics and earthquake hazards along the east coast are reviewed by *Seeber and Armbruster* [1988]. They point out that east coast earthquakes may cause more damage than west coast earthquakes of similar size. Data from the 1929 Grand Banks earthquake was reanalyzed by *Hasegawa and Kanamori* [1987] who found that a single force model, representing a submarine sediment slide, was most consistent with the P, S, and surface wave data. Submarine slides thus represent yet another source, in addition to active faults, which are likely to cause tsunamis along the eastern seaboard.

The 1983 (m_b=5.1) Goodnow, New York earthquake was well recorded by the local seismic network and by remote stations in the U.S., Europe, and South America [*Nabelek and Suarez*, 1989]. The focal mechanism exhibited reverse faulting at a 7.5 km depth on a north striking and west dipping fault. It also exhibited an unusually large stress drop of 265 bars [*Nabelek and Suarez*, 1989]. The 1984 (m_{blg}=4.1) Martic earthquake occurred within the Lancaster seismic zone in southeastern Pennsylvania and showed oblique reverse faulting on an east dipping fault [*Armbruster and Seeber*, 1987].

In a novel study *Seeber and Armbruster* [1987] searched for felt reports in newspapers published in South and North Carolina, Georgia and eastern Tennessee during 1886-1889. They reported more than 3000 new intensities associated with more than 522 aftershocks following the 1886 Charleston earthquake.

Causes of Intraplate Earthquakes

Three models of the origin of earthquakes in the central and eastern U.S. have been proposed. The first is the "zone of weakness model" [*Sykes*, 1978; Dewey et al., 1989], the second is the "local basement inhomogeneity model" [*Hinze et al.*, 1988], and the third is the "inducing with high pore-fluid pressures" model [*Sibson*, 1989].

After having relocated 270 earthquakes recorded by regional networks, *Gordon* [1988] concluded that these events were occurring along zones of crustal weakness. As a way of identifying zones of weakness or active faults in the central and eastern U.S., *Hamilton and Mooney* [1990] proposed to use the strong attenuation of seismic waves, which they reported for the New Madrid region.

Seismicity exterior to former rift basins may be caused by high stress due to lithospheric bending [*Dewey*, 1988]. Similarly *Kuang et al.* [1989] attributed seismicity in the southern Appalachians to crustal stress inhomogeneities, although they could not account for the seismicity in the Charleston area with similar stress anomalies. The 1982 (5.7>m_b>5.0) Miramichi earthquake sequence in northern New Brunswick may have been induced by high pore-fluid pressures at a depth of 7 km [*Sibson*, 1989]. He suggested that a mixed H_2O-CO_2 fluid of mantle origin is a possible cause of the inferred high pressure fluids.

SUBDUCTION ZONES

Subduction zone seismotectonics continue to be an active topic of study for many U.S. researchers. These studies are either focussed on analyzing data or constructing models to explain temporal and spatial distribution of seismicity.

To explain temporal and spatial seismicity patterns along and adjacent to the plate interface during the complete earthquake cycle, *Dmowska et al.* [1988] developed a model of pulsating and interacting stresses. A less complex plate sinking or slab pull model explains precursory seismicity at intermediate depth as well as the existence of double Benioff zones [*Spence*, 1987]. The upper limit of the down-dip width of the elastic-brittle plate interface in subduction zones occurs along the base but not at the top of an accreted wedge of young sediments [*Byrne et al.*, 1988].

Christensen and Ruff [1988] and *Lay et al.* [1989] analyzed and compiled a catalog of 1130 focal mechanisms of intraplate earthquakes which occurred in nine circum-Pacific subduction zones. They find that outer rise compressional events may be preshocks or be associated with seismic gaps. Conversely, outer rise tensional events in general follow large intraplate events. They also concluded that the subducting slab shows viscoelastic behavior in response to the temporally varying interplate stress regime.

Pacific Northwest

The slab geometry and earthquake potential of the Cascadia subduction zone beneath Washington and Oregon is being studied by several research groups. The change in strike of the trench causes the slab to be smoothly arched, with the crest of the arch beneath Puget Sound [*Crosson and Owens*, 1987; *Owens et al.*, 1988; *Weaver and Baker*, 1988]. The 1949 (M_S=7.1) south Puget Sound earthquake may have resulted from down-dip tension within the Juan Fuca Plate on the south side of the arch [*Weaver and Baker*, 1988]. This earthquake occurred at 54 km depth and showed left-lateral faulting on a 40 km long east striking plane dipping 45° to the north [*Baker and Langston*, 1987]. The state of stress in the Cascadia subduction zone is controlled by the interaction of the Pacific plate and the Gorda-Juan de Fuca-Explorer plate system with the overriding North America plate and some component of stress caused by the pull force of the sinking slab [*Spence*, 1989].

Alaska and Aleutian Arc

Three large (M_S=6.9, 7.6, and 7.6) strike-slip faulting earthquakes occurred from November 1987 to March 1988 in the northern Gulf of Alaska. These events were related to tensional stresses seaward of the 1964 (M_W=9.2) Alaska earthquake and to compressional stress caused by the collision of the Yakutat terrane with the North America plate [*Lahr et al.*, 1988].

The Aleutian and Wrangell Wadati-Benioff zones in southern Alaska are both continuous to depths of at least 45 km and appear to represent two limbs of a buckle in the subducted oceanic plate [*Page et al.*, 1989]. Reflected and mode-converted seismic waves from earthquakes located within the shallow Aleutian subduction zone along the southern Kenai Peninsula originate from the inferred interplate megathrust as well as from several other discontinuities [*Stevens et al.*, 1989]. In some cases underplated rocks may form these extensive reflectors.

Detailed studies of the earthquake potential of the Shumagin seismic gap continued. Relocation of 17 earthquakes of M>6.8 in the Aleutian Arc showed that a M_S=7.9 earthquake in 1917 may have ruptured a significant part of the Shumagin seismic gap [*Boyd and Lerner-Lam*, 1988]. Similarly, the deepest part of the western half of the gap may have ruptured in 1948 by M_S=7.5 event [*Boyd et al.*, 1988]. A double-planed Benioff zone exists only beneath the western half of the Shumagin gap. The east and west regions may thus either have different aseismic-to-seismic slip ratios or be independent rupture segments [*Hudnut and Taber*, 1987].

The 1986 (M_W=8.0) Andreanof Island earthquake was anticipated on the basis of seismic quiescence reported by the Adak Seismic Network [*Kisslinger*, 1988]. Seismicity before and following the 1986 event was studied in retrospect by *Engdahl et al.* [1989] and *Ekstrom and Engdahl* [1989] who showed that apart from the seismic quiescence the pre-mainshock seismicity gave few clues about the impending mainshock. *Das and Kostrov* [1990] inverted for the source parameters of the earthquake and found a total source duration of 80 s with most of the moment release occurring to the west of the hypocenter during the first 55 s. In an independent study, *Boyd and Nabelek* [1988] inverted long-period P and S waves for the source parameters of the earthquake and some of its aftershocks. They found a thrust focal mechanism for the mainshock on a plane dipping 23°. Some of the large aftershocks occurred within the upper plate and show right-lateral strike-slip faulting along a northeasterly trending fault.

Northwestern Pacific

The 1978 (M_S=7.5) Miyagi-Oki, Japan event was an underthrusting event beneath northern Honshu, which ruptured down to a depth of 40 km [*Tichelaar and Ruff*, 1988]. One of the largest underthrusting events to occur since the early 1960s was the great 1963 (M_W=8.5) Kurile Islands earthquake [*Beck and Ruff*, 1987]. This event ruptured a 245 km long segment of the plate boundary, with at least three asperities. In a detailed study of the seismic behavior of the southern Kurile Arc, *Schwartz et al.* [1989] showed that segmentation along strike may reflect the variation in depth of major asperities along the thrust zone.

Southeastern Pacific

A renewed interest in the 1960 great Chilean earthquake has included studies of a slow precursor of comparable size as the mainshock [*Cifuentes and Silver*, 1989; *Linde and Silver*, 1989] and the foreshock-mainshock-aftershock sequence [*Cifuentes*, 1989]. The 1985 (M_S=7.8) Central Chile earthquake involved rupture of strong asperities located near the down-dip end of the plate interface [*Choy and Dewey*; 1988; *Barrientos*, 1988].

Analyzing 708 earthquakes *Chowdhury and Whiteman* [1987] inferred a continuous undulating slab rather than a segmented slab beneath southern Peru and central Chile. Using a larger data set *Schneider and Sacks* [1987] suggested that significant plate extension occurs within the slab beneath southern Peru. Focal mechanisms for large earthquakes along the Peru Trench show both down-dip compression and tension, which reflect the complex slab geometry [*Beck and Ruff*, 1989].

Mexico

The short recurrence times of 30 to 60 yr for large or great earthquakes along the Mexican subduction zone make this plate boundary an attractive earthquake laboratory. The Ometepec segment ruptured in one M_S=8.0 earthquake in 1907 and again in three earthquakes in 1937, 1950, 1957 and 1962 [*Nishenko and Singh*, 1987]. The 1982 earthquake doublet, M_S=6.9 and 7.0, that occurred in the eastern half of the Ometepec gap was preceded by distinct seismicity patterns [*Gonzalez-Ruiz and McNally*, 1988]. A recent recompilation of the seismic strain release in the Mexican subduction zone during the 20th century shows that the Guerrero gap is the one most likely to have a future great earthquake [*Anderson et al.*, 1989].

Astiz et al. [1987] determined source parameters for large earthquakes that ruptured the Michoacan gap during 1981 to 1986. They found sequential failure of at least five asperities which all may have failed in the 1911 M_S=7.8 Michoacan earthquake. In a study of the 1985 Michoacan earthquake *Mendoza and Hartzell* [1989] identified three major asperities along the 150 km long rupture.

Southwestern Pacific

To determine the nature of crustal deformation in the Vanuatu Arc, *Taylor et al.* [1990] dated corals that suffered tectonic uplift both due to seismic and aseismic slip. They found that reported seismic moments account for only 10-30% of the slip associated with the ongoing subduction. On the basis of focal mechanisms and earthquakes *Cooper and Taylor* [1989] reported large-scale contortion and segmentation of the slab being subducted into the New Britain Trench.

The 1977 (M_S=6.8) Tonga arc earthquake was a slab decoupling, normal faulting event [*Lundgren and Okal*, 1988; *Zhang and Lay*, 1989]. The large 1986 Kermadec earthquake also was caused by internal deformation of the subducting Pacific slab at a depth of 40 km [*Lundgren et al.*, 1989]. Similarly, the great 1977 (M_W=8.2-8.3) Sumba earthquake that occurred within the Indian plate to the west of Australia was a normal faulting event [*Lynnes and Lay*, 1988].

To study the collision of Australian continental lithosphere along the eastern Sunda and Banda arcs, *McCaffrey* [1988] used data from 63 large earthquakes to infer the tectonics of this region. He found crustal shortening accommodated both by compression within the arc and over thrusting over the back arc basin. The Bali Basin is a downwarp in the crust of the Sunda Shelf caused by thrusting along the Flores back arc [*McCaffrey and Nabelek*, 1987].

Newcomb and McCann [1987] used historic records of the last 300 years and instrumental records for the last century to identify two great earthquakes that ruptured major segments of the Sumatra fore arc in western Indonesia. Focal mechanisms of large earthquakes located near the North Island of New Zealand reflect the transitional nature of the tectonics from convergent in the north to strike-slip in the south [*Dziak and Wesnousky*, 1990].

Oblique convergence and subduction exists in the Macquarie Ridge complex [*Ruff et al.*, 1989]. The 1989 (M_S=8.3) Macquarie Ridge earthquake that showed right-lateral strike-slip motion along the Pacific-Australia plate boundary was consistent with previous tectonic interpretations [*Ruff*, 1990; *Braunmiller and Nabelek*, 1990; *Ekstrom and Romanowicz*, 1990; *Satake and Kanamori*, 1990; *Tichelaar and Ruff*, 1990; *Houston*, 1990].

Several geophysical surveys have been conducted to constrain the plate interaction in and near Taiwan [*Hsu et al.*, 1987; *Hagen et al.*, 1988; *Hsu*, 1990]. Based on source parameters of 15 large earthquakes that have occurred in Taiwan over the last 25 years, *Pezzopane and Wesnousky* [1989] reported significant variations in the state of stress and an east-west shortening rate of 2.6-5.4 cm/yr. Both the May and November 1986 Hualien, Taiwan earthquakes occurred on steeply dipping reverse faults [*Hwang and Kanamori*, 1989]. *Roecker et al.* [1987] used arrival times from local earthquakes to determine the three-dimensional velocity structure beneath Taiwan. They find three main structural zones: 1) in the east the subducting Philippine oceanic plate; 2) in the south the subducting Eurasian plate; and 3) a low velocity zone beneath the main part of the Island.

China.

Seismotectonics in China and the Tibetan plateau and other areas in the far east continues to interest a number of U.S. researchers. Focal mechanisms of large earthquakes show that crustal shortening occurs normal to the margins of the Tibetan plateau and east-west extension within the plateau [*Molnar and Lyon-Caen*, 1989]. A crustal thickness of 63-72 km beneath the plateau is reported by *Holt and Wallace* [1990] based on P_{nl} waveforms. North of the plateau, *Nelson et al.* [1987] report north-south shortening of the Tien Shan mountain range, which underthrusts sediments and causes uplift of basement blocks.

The 1976 Tangshan earthquake occurred in the North China sedimentary basin that has evolved as a composite pull-apart basin in response to right-lateral strike-slip faulting [*Nabelek et al.*, 1987; *Chen and Nabelek*, 1988]. From a study of the 1976 Tangshan aftershock sequence *Shedlock et al.* [1987] concluded that the deformation caused by this sequence extended the basin in north-south direction.

RIDGE AND TRANSFORM BOUNDARIES

Centroid depths and focal mechanisms derived from waveform modeling for mid-ocean ridge earthquakes show that fast spreading ridges have normal faulting earthquakes with shallower depth than slow spreading ridges, and are consistent with lithospheric necking models for the origin of the median rift valley [*Huang and Solomon*, 1987; *Huang and Solomon*, 1988]. Earthquake swarms that have often been attributed to magmatism along the median rift may in many cases be caused by extensional tectonics and the formation of the flanks of the rift [*Bergman and Solomon*, 1990]. Seismicity that occurs along oceanic transform faults is often deeper than oceanic intraplate strike-slip earthquakes because of higher strain rates [*Bergman and Solomon*, 1988].

The diffuse distribution of epicenters and focal mechanisms support the interpretation that the Galapagos 95.5°W rift is propagating to the south [*Cooper at al.*, 1987]. The eastern end of the Azores-Gibraltar plate boundary, the Davie ridge near Madagascar, and the Horizon bank in the north Fiji basin are also characterized by scattered seismicity and complex morphology over an area several hundred kilometers wide [*Chen and Grimison*, 1989].

The 2-3 mm/yr plate convergence across the western boundary between the Eurasian and African plates has caused an unusually high rate of seismicity from the Azores Islands to Gibraltar [*Grimison and Chen*, 1988]. *Wilcock et al.* [1990] provided microearthquake evidence for extension across the Kane transform fault. They concluded that P-axes of microearthquakes also provide evidence for a low strength transform fault. Analysis of recent marine geophysical and earthquake data show that the African, North American, and Eurasian plates are rigid, and the Gloria fault is an active transform fault [*Argus et al.* 1989].

VOLCANIC SEISMICITY

The Puu Oo eruption of Kilauea volcano, Hawaii in 1983 and 1984 included both dike injection episodes into the rift zone as well as episodic eruptions. The distribution of the associated earthquake activity quantifies earlier theories about the structure of the magma transport system that feeds eruptions at Kilauea and the formation of dikes within the rift zone [*Koyanagi et al.* 1988]. Low coda-Q, pervasive faulting, high seismicity rate, and intermediate term precursory quiescence, and possibly low b-values all characterize a sub-volume of intense faulting within the Kaoiki aftershock area of southern Hawaii [*Scherbaum and Wyss*, 1990].

A single force model as opposed to a dislocation model does an adequate job of explaining data from the 1975 (M_S=7.1) Kalapana, Hawaii earthquake, suggesting that the event was more like a landslide than a normal faulting event confined to a half-space [*Eissler and Kanamori*, 1987].

The eruption activity of the Augustine volcano in the Cook Inlet Alaska during 1976 was characterized by a series of explosive vent-clearing pyroclastic eruptions [*Reeder and Lahr*, 1987]. A totally different style of eruptions is reported by *McNutt* [1987] for the Pavlof volcano, Alaska, which shows both magmatic eruptions of 1-2 days duration and phreatic-phreato-magmatic activity lasting several days to two months.

The tectonics and recent eruptions of Mount St. Helens, Washington are summarized by *Weaver and Malone* [1987]. The position of Mount St. Helens is related to the intersection of a right stepping offset in the St. Helens seismic zone and a set of older fractures, which may transport magma through the crust [*Weaver et al.*, 1987]. High quality locations of shallow earthquakes with almost identical waveforms represent repeated failure within a small volume adjacent to the highly strained magma supply conduit [*Fremont and Malone*, 1987]. In a tomographic inversion *Lees and Crosson* [1989] identified a low velocity anomaly at 6 to 16 km depth beneath Mount St. Helens and suggested that may be related to subsurface magma chamber.

The earthquake activity and crustal deformation within the Long Valley caldera in eastern California that began in 1980 still continues [*Rundle and Hill*, 1988]. Some of the more recent activity in Long Valley was a swarm of small earthquakes during 1989 at 6 to 9 km depth beneath Mammoth Mountain [*Hill et al.* 1990].

The 1986 Chalfant California earthquake that was located just southeast of the Long Valley caldera was the third significant earthquake to occur in California during 1986. It was preceded by a significant foreshock sequence that occurred on a conjugate plane relative to the mainshock [*Smith and Priestley*, 1988]. Teleseismic source parameters of the mainshock show strike-slip faulting with a small normal component and three asperities which broke during the first 4 s of rupture [*Pacheco and Nabelek*, 1988].

Beneath Indian Wells Valley low P and S velocities, high V_P/V_S, and anomalous SV attenuation are interpreted to be caused by partial melt [*Walck and Clayton*, 1987; *Ho-Liu et al.*, 1988; *Sanders*, 1988; *Walck*, 1988]

CONCLUSIONS

During 1987-1990 significant progress has been made in understanding deformation adjacent to the San Andreas fault. The deformation around the fault in the Coast Ranges in central California is probably best understood while deformation near the fault in southern California is least well understood. The occurrence of the 1989 Loma Prieta earthquake along the San Andreas fault demonstrated that the concept of characteristic earthquakes may not apply even to this fast moving fault and that the deformation is more complex than previously assumed. In addition to fault segmentation, geological slip rate, and time since the last earthquake, parameters such as rupture direction and possibly fluid flow are important for determining rupture length and hence recurrence interval [*Sibson*, 1989].

Some progress in understanding intraplate earthquakes has been made. The three possible models for the occurrence of intraplate earthquakes, zones of weakness, basement inhomogeneity, and induced seismicity, can be continually tested with data from the numerous well recorded M=4-5 earthquakes. Understanding the processes that generate stresses and the possible stress memory of the continental crust, however, will require extensive space geodetic measurements as well as continued earthquake monitoring for decades to come.

The kinematics of the brittle subducting slab are better understood through studies of several great normal faulting earthquakes, which may have ruptured through the slab. Identification of slip partitioning between strike-slip faults in the upper plate and the megathrust provides a mechanism for accommodating oblique motion in subduction zones [*Ekstrom and Engdahl*, 1989]. The seismicity during a complete earthquake cycle can in some cases be explained with asperity or stress diffusion models, although the applicability of such models is still the subject of intense research efforts.

The seismic monitoring of the 1989-1990 Redoubt volcano in Alaska demonstrated how our understanding of seismic tremors and other types of volcanic seismicity can be applied real-time to mitigate volcanic hazards [*Alaska Volcano Observatory staff*, 1990]. This and other recent eruptions have also provided new data for furthering research on volcanic seismicity.

Future research in seismotectonics will address both new and old problems. Some of the new problems that will get attention are: 1) what is the plate driving force (such as convective flow in the upper mantle), which controls the crustal deformation within plates and along plate boundaries? 2) what controls how much of the plate boundary deformation is released seismically in earthquakes and how much is released aseismically through creep? 3) what determines the width and configuration of distributed continental plate boundaries?

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